

Response of a TeO_2 bolometer to α particles

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ABSTRACT: TeO_2 crystals are used as bolometers in experiments searching for Double Beta Decay without emission of neutrinos. One of the most important issues in this extremely delicate kind of experiments is the characterization of the background. The knowledge of the response to α particles in the energy range where the signal is expected is therefore a must. In this paper we report the results on the response function of a TeO_2 bolometer to α 's emitted by ^{147}Sm dissolved in the crystal at the growth phase. A Quenching Factor of (1.0076 ± 0.0005) is found, independent of the temperature in the investigated range. The energy resolution on α peaks shows a standard calorimeter energy dependence: $\sigma [\text{keV}] = (0.56 \pm 0.02) \oplus (0.010 \pm 0.002) \sqrt{E[\text{keV}]}$. Signal pulse shape shows no difference between α and β/γ particles.

KEYWORDS: Bolometers; Quenching Factor; TeO_2 ; Double Beta Decay.

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1. Introduction

Bolometric detectors [1, 2] are used in particle physics experiments to search for rare events like Neutrinoless Double Beta Decay and Dark Matter interactions. They are sensitive calorimeters operated at ~ 10 mK that measure the temperature rise produced by the energy deposited in particle interactions.

An array of bolometers made of TeO₂ crystals has been used in the CUORICINO experiment [3, 4] to search for the Neutrinoless Double Beta Decay of ^{130}Te . A precise knowledge of the response function of these bolometers to each species of particles (β/γ and α) is important for the background rejection. Indeed, a sizeable fraction of the background in the Double Beta Decay Region of Interest (RoI), that for ^{130}Te is around 2.5 MeV [5, 6], is due to degraded α particles that lose part of their energy in the detector support structure and the rest in a single bolometer mimicking a signal event.

While the response of TeO₂ crystals to γ interactions up to 2.6 MeV is well known from the routine calibrations performed with Th radioactive sources, there are still relevant items that should be addressed for α particles. The most important are the Quenching Factor (QF), the relative energy resolution and, finally, possible signal shape differences with respect to γ/β interactions particularly in the region where the signal is expected.

The QF is defined as the amplitude ratio between the signal produced by an α particle and the one produced by an electron depositing the same energy in the detector. It is expected to be very close to unity in thermal detectors since any kind of energy deposition should be converted into heat.

The α 's that can be normally measured in the bolometer are either coming from decays inside the crystals or by interactions induced by external sources. Those coming from internal contaminations (usually from U and Th chains) have energies higher than 4 MeV, well above the Double Beta Decay region of interest.

The QF for α particles in the energy region [5.7-8.8] MeV was measured in TeO₂ detectors [7] using a ²²⁸Ra α radioactive source. It was found to be $1.020 \pm 0.005(stat) \pm 0.005(syst)$. No deviation from constancy of QF as a function of energy has been observed. Nevertheless this measurement is based on an extrapolation of the calibration function at energies well above the region attainable with a Th source (2.6 MeV), where non-linearities of the TeO₂ bolometers play an important role [8].

In this work we studied the response of TeO₂ bolometer to an internal source producing monochromatic α particles with energy close to the Q-value of ¹³⁰Te Neutrinoless Double Beta Decay. We achieved this goal dissolving into a TeO₂ crystal a small amount of natural samarium. The naturally occurring isotope ¹⁴⁷Sm has an isotopic abundance of $(15.0 \pm 0.2)\%$ [11] and an half life of $1.06 \cdot 10^{11}$ y [11]. To have a reasonable α decay rate (\sim count/hour) the crystal should contain only a few micrograms of natural Sm.

The α particles are emitted in the ¹⁴⁷Sm \rightarrow ¹⁴³Nd + α transition. The Q-value of this reaction is shared between the emitted α particle and the recoiling nucleus. Since the decay is contained within the crystal, we measure the full transition energy of (2310.5 ± 1.1) keV [11, 12].

Beside the obvious advantage of measuring the α response in the actual RoI, an additional yet extremely relevant feature is present and could be fruitfully exploited. Bolometers, in fact, require a continuous monitoring of the operating temperature. Even tiny drifts can induce variations of the thermal gain, thus spoiling the energy resolution. To correct for this effect, a Si resistor (heater) glued to the detector surface produces heat pulses by Joule dissipation which are very similar to particle induced pulses and the temperature drift can be corrected offline on the basis of the measured heater pulse amplitude variation [9, 10]. Heaters however can experience electronic failures or grounding problems, resulting in changes of their pulse amplitude not related to temperature drifts. This calls for a frequent re-calibration of the entire system that is obviously a long time subtracted to physics data taking.

The presence of a long-lived monochromatic α line in the proximity of the RoI could take the role of the heater and allows less frequent calibrations.

The outline of this work is the following: in Section 2 general properties of TeO₂ crystals and the doping process with natural Sm are described, in Section 3 details of the experimental setup are given while results are summarized in Section 4.

2. Doping of TeO₂ crystal with an α -particle emitter

Two methods are currently used for growing TeO₂ crystals: Czochralski and Bridgman. The growth is rather difficult, special temperature gradient conditions as well as pulling and/or rotating rates being needed in order to obtain high quality crystals. Further post-growth thermal treatments are applied to the as grown ingots aimed at quenching the tendency of TeO₂ single crystals to cracking caused by high anisotropy of thermal coefficients. Inhomogeneities in the crystal due to the incorporation of Pt dissolved from the crucible is another problem frequently reported [14] and careful control of convection currents in the melt is needed to avoid the incorporation of the gas bubbles to the crystals, especially in the case of Czochralski growth.

TeO₂ crystals do not easily permit impurities inclusion in the lattice. The paratellurite structure, especially the asymmetric covalent Te-O bonds, limits the incorporation of the dopants to

extremely low levels which results in very low segregation coefficients ($k \sim 10^{-2}$). To avoid precipitation or aggregation of foreign ions during crystal growth only small amounts of dopant can be added to the melt and the resulting built-in concentration is often below the limit for chemical analysis [14]. Only a few successful doping of TeO_2 are reported in literature for ions like Fe or Cr [15] and Mg, Mn, Nb, Zr [16]. As a general rule for selecting the α dopant, two criteria should be taken into consideration: radioactive properties of the nuclide and the incorporation to the host lattice of the ion.

In our particular case, where the detector has to be applied to the search for very rare events, supplementary constraints are imposed on the radio-purity of the chemical compound used for the doping. Moreover, for cryogenic applications of TeO_2 crystals, the incorporation of uneven ions in the TeO_2 lattice is to be avoided because of the possible problems of cooling paramagnetic materials at very low temperatures.

The Sm doped crystal reported in the present work was grown by a modified Bridgman method described in detail in [17]. For the growth, 6N purity TeO_2 powder was used. Tellurium oxide raw material was synthesized at SICCAS, Shanghai China, in a process described in detail in [18]. The crystal was grown in a dedicated furnace used for R&D purpose where ingots of typically 30 x 25 x 120 mm can be obtained. The crystal growth followed the protocol described in detail in [19]. Sm dopant was added to the raw material powder in oxide form using Sm_2O_3 powder of 6N purity. The doping process was performed in two steps. The $\text{Sm}_2\text{O}_3/\text{TeO}_2$ powder was first melted in order to obtain an ingot of homogeneous oxides mixture from which a small sample was taken and used as dopant for the final crystal growth with a nominal dopant concentration of $5 \cdot 10^{-6}$ g/g of $\text{Sm}_2\text{O}_3/\text{TeO}_2$. A charge of approximately 400 g (crystal seed excluded) was used for the final growth which resulted in an ingot of approximately 65 cm^3 . The grown ingot was colorless and free of cracks, bubbles and/or inclusions except for a small region due to a thermal instability during the growth process (see Fig. 1). It was subjected to special post-growth thermal treatment in order to avoid cracks during mechanical processing. A sample of approximately 30x24x28 mm^3 ($m=116.65$ g) was extracted for cryogenic measurement from the region no.4 of the as grown crystal. The sample was cut and X-ray oriented with a precision better than 0.5° following the procedure described in [19] except for the chemical etching. Different samples were taken from each region (1 to 6) for ICP-MS measurements aimed at checking the general quality of the crystal and especially the uniform distribution of dopant along the growth direction. ICP-MS measurements were made using an "Agilent Technologies 7500 Series" instrument [19]. The measurements were made on samarium isotopes free of instrumental interferences: ^{149}Sm , ^{152}Sm and ^{154}Sm . For each isotope the Sm concentration was inferred assuming the natural abundance. The mean value is found to be of the order of 30 ppb which gives for the 116.65 g sample approximately 3.5 μg Sm.

3. Experimental set-up and Data Acquisition

The Sm doped TeO_2 crystal was operated in a cryogenic setup located deep underground in the Hall A of National Laboratory of INFN at Gran Sasso.

The crystal was equipped with two Neutron Transmutation Doped Ge thermistors (NTD) [20] of $3 \times 3 \times 1$ mm^3 , thermally coupled to the crystal surface with 9 epoxy glue spots (~ 0.8 mm diameter). The electrical conductivity of NTD, which is due to variable range hopping (VRH) [21]

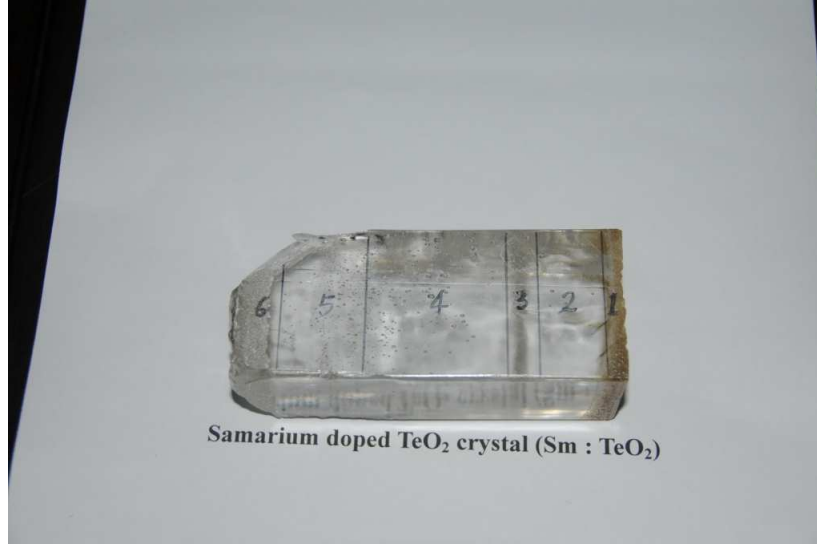


Figure 1. Sm doped TeO_2 crystal as grown. Different samples were cut for analysis. The cloudy (no. 3) region is due to a thermal instability during the growth process.

of the electrons, depends strongly on the temperature. The resistance changes with temperature according to [22]

$$R = R_0 \cdot e^{\left(\frac{T_0}{T}\right)^{1/2}} \quad (3.1)$$

and then resistance variation can be used to measure effectively the heat signal produced by interacting particles. The R_0 and T_0 of the two NTDs were measured to be respectively $\sim 1\Omega$ and $\sim 3\text{K}$. At the working temperature of $\sim 10\text{ mK}$ the value of R is $\sim 100\text{ M}\Omega$.

A resistor of $\sim 300\text{ k}\Omega$, realized with an heavily doped meander on a $2.33 \times 2.4 \times 0.6\text{ mm}^3$ silicon chip, was glued to the crystal and used as a heater to stabilize the gain of the bolometer.

The crystal was mounted in an Oxygen Free High Conductivity (OFHC) copper structure and kept in position by PTFE tips. The L shape of the PTFE pieces was chosen to profit from the high thermal contraction of the Teflon keeping tightly the crystal.

Finally, the detector was mounted and operated at $\sim 10\text{ mK}$, cooled by an Oxford 1000 $^3\text{He}/^4\text{He}$ dilution refrigerator. The crystal holder was mechanically decoupled from the cryostat in order to minimize noise vibrations induced by the cryogenic facility. A weak thermal coupling between the mixing chamber of the dilution refrigerator and the crystal holder was realized by means of thin high conductivity copper strips. The holder was also equipped with one NTD thermometer and one heater. In this way it was possible to stabilize the temperature of the crystal holder using a feedback device [23].

The cryostat was heavily shielded both internally and externally in order to decrease the γ background on the detector coming from radioactive materials. Below and above the detector there was a $\sim 10\text{ cm}$ thick layer of low-activity ancient Roman lead [24, 25]. Around the sides of the detector holder an additional 1.2 cm thick cylindrical Roman lead shield was present. The cryostat was surrounded by an additional external shielding composed by 10 cm low-activity lead, 10 cm standard lead followed by 10 cm borated polyethylene. The latter allows to reduce the neutron flux

on the detector thanks to the high efficiency in thermalizing fast neutrons and to the high neutron capture cross section for thermal neutrons of ^{10}B . The entire setup was enclosed in a Faraday cage to reduce electromagnetic interference.

The thermistors were biased through two room temperature $27\text{ G}\Omega$ load resistors. The large ratio between their resistances and those of the thermistors allows to have negligible parallel noise.

The read-out of the thermistors was performed through a room temperature DC coupled differential front-end [26] followed by a second stage of amplification both located on the top of the cryostat. After the second stage, and close to the DAQ (a 18 bit NI-PXI 6284 ADC unit), a 6 pole roll-off active Bessel filter acted as antialiasing filter.

The entire waveform of each triggered pulse was sampled with a rate of 1 kHz and recorded. The typical bandwidth is approximately 10 Hz, with signal rise and decay times of order of 40 and 200 ms, respectively.

The two thermistors are read by independent electronic channels and will be denoted in the following as Channel 1 and Channel 2.

A more detailed description of the electronics and the cryogenic facility can be found in Ref. [3, 4].

4. Data Analysis and Results

Two separate sets of data have been collected at different holder temperatures (run1: $\sim 10\text{ mK}$, run 2: $\sim 15\text{ mK}$) in order to investigate possible temperature dependencies of the Quenching Factor and differences of the pulse shape between α and β/γ particles.

The energy calibration is performed using four ^{232}Th γ sources inserted inside the external lead cryostat shield. The pulse amplitude (A) is estimated by means of an Optimum Filter technique [27]. The Channel 1 calibration spectrum in run 1 is shown in Fig. 2. Gamma lines from the ^{232}Th decay chain are visible in the spectrum and listed in Table 1. The ^{147}Sm α line is also clearly visible as well as another α line at 5.407 MeV from ^{210}Po . This contamination originates during the crystal growth. The line from ^{210}Po is not considered in our QF calculation since it lies in an energy region where the calibration is not reliable at the desired level of accuracy.

The calibration peaks are fitted using a Gaussian function + linear background.

Isotope - source	Energy [keV]
$e^+ e^-$ annihilation	511.0
^{208}Tl	583.2
^{228}Ac	911.2
^{228}Ac	968.9
2614.5 keV DE	1592.5
2614.5 keV SE	2103.5
^{208}Tl	2614.5

Table 1. Calibration peaks from the ^{232}Th source.

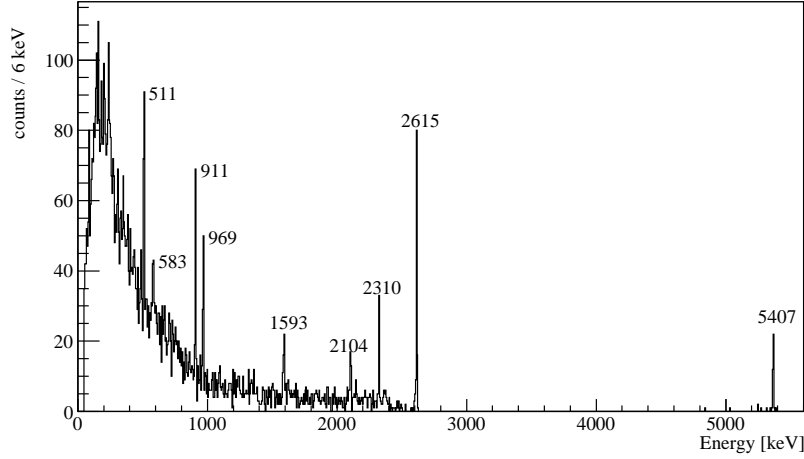


Figure 2. Calibration spectrum of Channel 1 - run 1. The calibration is performed with external ^{232}Th γ sources. The main peaks used for calibration are labeled together with the ^{147}Sm α line at 2310 keV and the ^{210}Po α line at 5407 keV.

The calibration function is a third order polynomial with zero intercept. The Quenching Factor is extracted from a simultaneous fit to the γ 's and the α line adding the QF as a free additional parameter. To properly take into account uncertainties on fitted amplitudes (A_i) and transition energies (E_i), the following likelihood function has been minimized:

$$-\log \mathcal{L} = -\sum_i \log \frac{1}{\sqrt{2\pi}\sigma_i} e^{-\left(\frac{E_i - P(A_i)}{\sqrt{2}\sigma_i}\right)^2} - \log \frac{1}{\sqrt{2\pi}\sigma_\alpha} e^{-\left(\frac{E_\alpha - P(A_\alpha)/QF}{\sqrt{2}\sigma_\alpha}\right)^2} \quad (4.1)$$

where the index runs over the calibration peaks, $P(A)$ is the polynomial calibration function to be estimated and $\sigma_{i,\alpha}$ is computed as:

$$\sigma_{i,\alpha} = \sqrt{\sigma_{E_{i,\alpha}}^2 + \left(\frac{\partial P}{\partial A} \sigma_{A_{i,\alpha}}\right)^2} \quad (4.2)$$

The QF calculated for both channels and runs is reported in Table 2. The correlation between the QFs has been evaluated on the energy distribution of coincidence events in the α peak, recorded simultaneously by the two channels. Taking into account the full covariance matrix, a $QF = 1.00755 \pm 0.00066$ and $QF = 1.00765 \pm 0.00066$ is found for run1 and run2 respectively. The error is dominated by the uncertainty on the ^{147}Sm Q-value. No temperature dependence is observed; the average QF is 1.0076 ± 0.0005 .

4.1 Energy Resolution and Pulse Shape

We have performed a study on the dependence of the energy resolution of the γ (^{232}Th) and the α (^{147}Sm and ^{210}Po) peaks as a function of energy.

The Optimum Filter [27], used for amplitude estimation, reduces the noise superimposed to the signal, maximizing the signal to noise ratio. The ultimate resolution is governed by the noise

Run	Channel	QF	QF error
1	1	1.0076	0.0007
1	2	1.0075	0.0007
2	1	1.0078	0.0007
2	2	1.0075	0.0007

Table 2. QF calculated for the two channels for both runs. The error is dominated by the uncertainty on the ^{147}Sm Q-value (see Introduction).

at the filter output, and does not depend on the pulse amplitude. We estimated this resolution, σ_{OF} , on data samples recorded randomly and without triggered events.

The energy resolution of α and heater peaks has been calculated with Gaussian + linear background fits (see for example the fit on the ^{147}Sm line in Fig. 3). The quantity σ^2 is shown as a function of energy in Fig. 4. The squared heater resolution σ_H^2 (black triangle) is well consistent with σ_{OF}^2 (dashed line), indicating that no physical process other than the noise contributes to it. On the other end, the resolution of α lines lies above σ_{OF}^2 and exhibits a dependence on the energy.

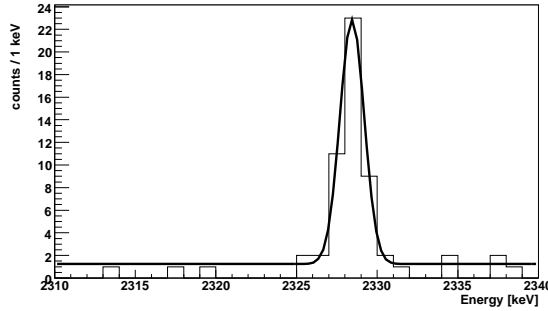


Figure 3. Gaussian + linear background fit of the ^{147}Sm line for Channel 1 - run 2. The energy (not corrected for the Quenching Factor) is (2328.4 ± 0.14) keV, with resolution of (0.75 ± 0.12) keV.

A linear fit on the α points of Fig. 4 is performed, assuming that the resolution at zero energy is equal to the heater resolution (σ_H^2) with the corresponding error. The energy dependence of the α resolution is well in agreement with the behavior of a calorimeter, where not all the energy is eventually collected:

$$\sigma [\text{keV}] = (0.56 \pm 0.02) \oplus (0.010 \pm 0.002) \sqrt{E[\text{keV}]}.$$

This behaviour indicates that in a macrobolometer, where all the energy is expected to be transformed into heat and measured, some phenomena are responsible for a missing part. We performed the same analysis on Channel 2 and found a consistent energy dependence: $(0.012 \pm 0.003) \sqrt{\text{keV}}$.

A more intriguing feature emerges from the energy resolution measured on the ^{208}Tl γ line. Its value is worse than the one of an α line of equivalent energy:

$$\begin{aligned} \sigma_{Tl}^2 &= (5.9 \pm 2.3) \text{ keV}^2 \\ \sigma_{\alpha(2614.5 \text{ keV})}^2 &= (0.6 \pm 0.1) \text{ keV}^2 \end{aligned}$$

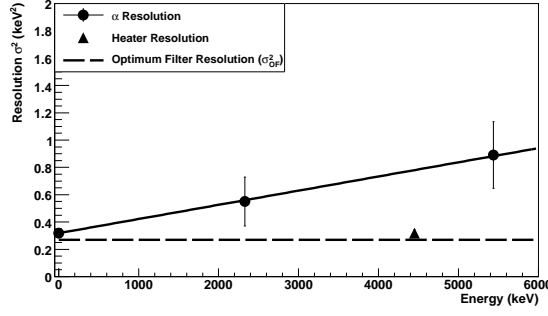


Figure 4. Squared energy resolution (σ^2) for α 's (dots) and heater (triangle) as a function of energy for Channel 1 - run 2. The theoretical Optimum Filter resolution (σ_{OF}^2) is shown for comparison (dashed line). The linear fit on α points is performed assuming that the resolution at zero energy is equal to the heater resolution (σ_H^2) with the corresponding error.

The crystal is however too small and the statistics too limited to allow a detailed study of the energy resolutions of the β/γ branch.

We investigated the difference in pulse shape between α and β/γ particles. In bolometric detectors the shape of the signal is not constant with energy as detailed in [8]. Shape parameters, therefore, have been compared for events in the ^{147}Sm α peak ([2320-2334] keV) and in the sideband regions ([2200-2320] keV, [2340-2460] keV), mainly populated by β/γ 's.

The rise and decay times, computed as the time difference between the 10% and the 90% of the leading edge and the 90% and 30% of the trailing edge respectively, are reported in Table 3. The error is dominated by the resolution of the sampling period. No difference is found within the error.

Particle	Rise Time [ms]	Decay Time [ms]
α	49.0 ± 0.4	219.6 ± 0.4
β/γ	49.0 ± 0.4	219.9 ± 0.4

Table 3. The rise and decay times for α and β/γ particles in the ^{147}Sm α region and in the sideband regions.

5. Conclusions

We characterized the response function of a TeO_2 bolometer to α particles with energy close to the Q-value of the ^{130}Te Neutrinoless Double Beta Decay. To achieve this goal we dissolved into a TeO_2 crystal a small amount of $^{\text{nat}}\text{Sm}$ at the growth phase.

A Quenching Factor for α particles of (1.0076 ± 0.0005) is found, independent of the temperature in the investigated range.

The energy resolution on α peaks shows a standard calorimeter energy dependence: $\sigma [\text{keV}] = (0.56 \pm 0.02) \oplus (0.010 \pm 0.002) \sqrt{E[\text{keV}]}$. Resolution on a γ peak is found to be worse compared to an α line of equivalent energy, but the crystal is too small and the statistics too limited to draw any conclusion. Signal pulse shape shows no difference between α and β/γ particles.

Finally, the presence of a long-lived monochromatic α line in the proximity of the ^{130}Te Double Beta Decay RoI, could be used to correct thermal gain variation thus allowing less frequent calibrations.

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